Corrosive Sulphur and DBDS in Transformer Oil: Risk Assessments and Mitigation Actions on Power Transformers and Reactors - Utility Experience

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Abstract: ***Research by certain international agencies/ laboratories, following the failure of many high voltage equipment in different parts of the world, have led to the finding that copper sulphide produced by the reaction of DBDS with bare copper/ winding conductor could reduce the dielectric strength of the paper insulation, eventually resulting in breakdown of the equipment. Considering the novelty of the phenomenon and the potential threat imposed on transmission equipment, Dubai Electricity and Water Authority conducted a study to identify & assess the risk to equipment and take necessary actions to mitigate the risk. This paper describes the strategic approach and the results of the study as well as implementation and the current status of the mitigation actions.***

Keywords: Corrosive Sulphur, Copper Conductor, Copper Sulphide, Thermal Aging, Oil-paper insulation, Transformer, Reactor, Mitigation, Passivation, Reclamation, Adsorbent, Replacement

1. Introduction

Sulfur is commonly found in crude oil sources, as it comprises almost 0.05% of the earth's crust [3]. The transformer mineral oil is one of the sources for the formation of copper sulfide. The natural sulfur in insulating oil is present in the range of 0.001 to 0.5%. It was seen that the sulfur was also added intentionally to the oil in the form of an antioxidant such as Di Benzyl Disulfide DBDS to improve its thermal stability. Oil is not the only material that contains sulfur. Sulfur compounds are also present in the gaskets, some water-based glues, copper and paper insulation used in the manufacture of transformers. Sulfur can also be introduced into the transformer through accidental means such as through the use of incompatible hoses.

The insulation system in most power transformers and reactors consists of oil/paper on the copper windings, and there are also several oil-impregnated pressboard barriers between the high and low voltage windings, and between windings and the core [3]. Copper has stable physico-chemical properties, low electrical resistivity and is widely used in power transformers. Di Benzyl Disulfide (DBDS) is one of several sulfur compounds known to cause copper corrosion in transformers under certain circumstances. The mechanism of copper sulphide formation has been discussed in details in [4], [5]. The corrosive sulfur is formed by the reaction of DBDS with the copper surface. Breakdown of the DBDS to benzyl mercaptan or a DBDS Copper complex can cause corrosion of copper and the formation of copper sulfide over a wide temperature range from 80°C to 150 °C. This copper sulfide gets deposited on copper conductors and diffuses through the oil-paper insulation, followed by absorption of these intermediate compounds in paper. Copper being conductive reduces the dielectric strength of the paper insulation, thereby causing the transformer/ reactor to fail. In order to prevent the failure of an expensive asset, carrying out mitigation actions against Corrosive Sulphur and DBDS are deemed essential. Each asset owner/ operator are needed to evaluate their own level of risk and adopt an appropriate strategy to manage it. The first mitigation technique involves acting directly on the equipment as reconsidering the loading strategies, de-rating, improving the cooling efficiency and adding metal passivators. The second option concerns mineral oil itself and includes oil change and application of different oil treatment processes which may include physical process, i.e. removal of Corrosive Sulphur compounds from the oil by adsorption or extraction, using activated adsorbents or solvents, or chemical processes with reagents which are decomposing Sulphur compounds. A combination of these processes may also be used [4]. Each process offers its own advantages and disadvantages. The selection and success of the mitigation technique depend on several factors including information about the design of transformer, loading conditions, etc. Selection of the right mitigation actions can improve the life of the asset, thereby improving the reliability of the network, preventing expensive downtimes, better utilization of the existing asset, resulting in cost benefits over the life cycle.

2. Experimental Tests

Identification of the contamination done by qualitative method (Potential corrosive sulfur as per IEC 62535 [1]) and quantitative method (measurement of DBDS as per IEC 62697 [2]) as per the below tables.

Table 1: Qualitative Tests at Dewa Lab

	132 kV Reactors	400 kV Transformers	132 kV Transformers	Total
No of Oil Samples Tested	46	32	264	342
No of Oil samples found with Potentially Corrosive Sulphur	24	13	164	201

Table 2: Quantitative Tests at External Labs

	132 kV Reactors	400 kV Transformers	132 kV Transformers	Total
No of Oil Samples Tested Positive for Potentially Corrosive Sulphur	**24**	**13**	**164**	**201**
No of Oil samples found with DBDS >10 ppm	**19**	**4**	**150**	**173**

3. Discussion and Results

Upon discovering the global issues faced by several utilities, the research done by several groups and individuals and understanding the severity of the problems caused due to the contamination of Corrosive Sulphur & DBDS, DEWA Transmission Power T(P) Division decided to take proactive actions to mitigate its effect on assets. In order to achieve this, a study was carried out with the steps as below:

3.1 Detection of assets with DBDS and Corrosive oil

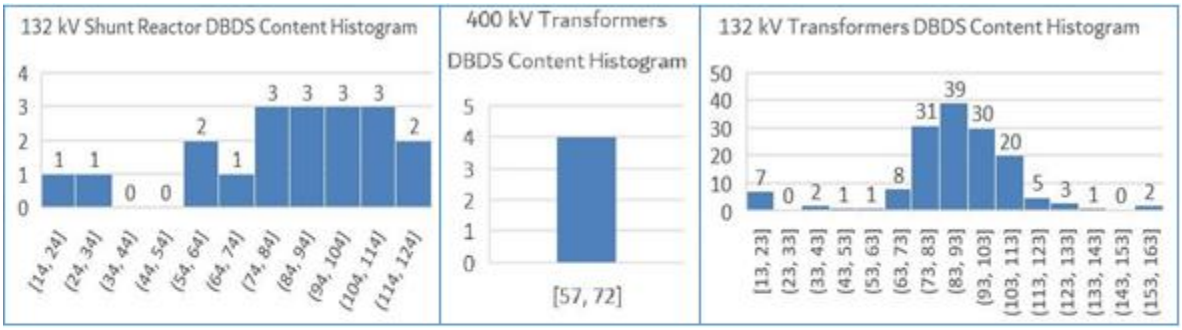
Based on the information available, it was clear that many of the oil refiners/transformer oil producers worldwide have been using, until the year 2006-07, an additive called Di-benzyl Di-sulphide (DBDS) in the oil to improve its thermal stability. Hence, priority for testing was given to assets that were commissioned before 2007. Eeventually all the assets would undergo this screening; however, considering the large asset database of T(P) the assets commissioned after 2007 were considered for the later phase. Having an in-house facility to test the Potentially Corrosive Sulphur (qualitative), T(P) carried out the qualitative tests, the summary of results of which is shown in Table-1 above.

One reason for testing negative for Potentially Corrosive Sulphur may be attributed to the presence of metal passivator in oil, the mechanism for which will be discussed later on.

In addition, it is an established fact that DBDS in oil reacts with copper to form copper sulphide and gets deposited/ diffused on copper and insulation (based on several conditions as per the mechanism of copper sulphide formation). Hence, an oil sample tested negative for Potentially Corrosive Sulphur does not ensure that the asset is not affected. It may happen that originally, the oil was contaminated with DBDS and this was consumed over the period of time to form copper sulphide deposits and the asset has been contaminated. However, having no means currently to measure the copper sulphide deposition (amount of deterioration already caused by Corrosive Sulphur), there is no way to identify if the asset which is tested negative is affected or not and more importantly how severe is the formation of Copper Sulphide.

Moreover, the presence of DBDS or copper Sulphide does not affect any of the other oil test results or can be related to any specific DGA gassing pattern, making it almost impossible to identify without invasive procedures. Based on the in-house test results, the positive samples (along with other random negative samples) were sent to three external labs for a quantitative test, the summary of results of which is shown in Table-2 above.

The distribution of DBDS content was found varied for all categories of equipment ranging from 13 ppm to 158 ppm as shown in the charts below. A DBDS concentration of 10 ppm was considered the threshold for the possibility of copper sulphide deposition. Assets with <10 ppm DBDS are considered under no risk and needed no actions.



With this extensive testing, T(P) prescreened all the suspected equipment and identified the equipment which are under risk of copper sulphide formation.

3.2 Prioritizing the equipment for mitigation actions

Out of 342 equipment, a total of 173 equipment were found with corrosive oil containing DBDS >10 ppm. However, apart from the level of DBDS concentration, based on the factors influencing the copper sulphide formation it was seen that the assets which are heavily loaded (high temperatures) and those with EHV windings (strong dielectric fields) are at the maximum risk. In addition, the criticality of the asset to the Transmission network was also considered as an influential factor by T(P).

Based on the above factors screening of all the 173 equipment was done and it was identified that the assets to be prioritized for mitigation action are 132 kV Shunt Reactors, since these are always operating at full load conditions and 400 kV Transformers based on their voltage rating and their criticality to the network. 132 kV Transformers were exempted from the first batch based on the above criterion.

Having no previous experience with mitigation action against Corrosive Sulphur and DBDS and with the several failures encountered by other utilities after carrying out mitigation actions (especially passivation), there was felt a need to further shortlist only the assets under extreme risk. To further filter out the 19 reactors and 4 nos 400 kV Transformers the additional criteria were applied based mainly on the "Flow chart for decision making associated with corrosive oil and risk of on-going Cu2S formation" [5]:

a) Whether the winding conductors were enameled: If the conductors were enameled, almost negligible copper surface is exposed, thereby reducing the chances of DBDS reaction with copper and formation of copper sulphide.
b) Oxygen content in oil/ Oxidation of oil: Low oxygen content in oil was seen as an accelerator of copper sulphide formation. Oxidation reactions cause formation of oxygenated Sulphur species, copper oxides, peroxides, copper hydro-peroxides, carbonyl and acidic compounds, which can be involved in copper sulphide formation as intermediate compounds [4]
c) Age of the asset: Older assets were considered to be at higher risk than their counterparts, owing to the aging of the oil and more importantly the insulation system.
d) DGA abnormality indicating local/ diffused overheating: In addition to the temperature/ load factor, any DGA abnormality indicating local or diffused overheating may result in concentrated formation and deposition of copper sulphide.

After applying all the above criterion, 4 nos 132 kV Bus Reactors in 400 kV Substations, 3 nos 132 kV feeder reactors & 1 no 132 kV bus reactor in 132 kV Substations and 2 nos of 400 kV Transformers were selected for the first phase of mitigation actions.

3.3 Selection of Mitigation actions

A filtration method has not yet been developed to successfully remove all corrosive sulfur compounds [6].The available mitigation techniques can be broadly classified in two categories [4] as below and T(P) was faced with a challenge of selecting the most suitable technique, considering the risk, performance and cost.

a) Techniques involving acting directly on the asset such as reconsidering loading strategies, such as derating the transformer or improving the cooling efficiency (reducing the temperature) and addition of metal passivator to cover copper and other metallic surfaces in the active part. Reconsidering loading strategies was not considered practicable for T(P) considering the huge number of equipment involved.
b) Techniques involving acting directly on the oil such as oil replacement or oil regeneration (physical process involving removal of Corrosive Sulphur compounds from the oil by adsorption or extraction) or chemical processes with reagents, which decompose Sulphur compounds or a combination of these.

In order to evaluate the mitigation techniques, feedback was obtained from leading Power Transformer manufacturers and few utilities regarding their recommendations and their experiences with the mitigation techniques executed (if any). The recommendations and experience provided an insightful picture of the various mitigation techniques.

Based on the above and T(P) Divisions' analysis of the mitigation techniques at that time, it was found that each technique has its own pros and cons as listed below. Moreover, there is no single solution that fits all, and several operational and strategic aspects needed to be taken into account while selecting the mitigation actions.

Key Factors	Mitigation Methods			
	Adding Metal Passivator to existing oil	Oil Reclamation	Oil exchange with addition of Metal Passivator	Chemical Process
Removal of DBDS	No (inhibits further reaction of DBDS on copper)	Claim to achieve almost complete removal	Partial removal (does not remove DBDS from insulation)	Claim to achieve almost complete removal
Cost	Low	Medium	High	Medium
Complexity	Simple	Medium	Medium	Complex
Time Consumption	Low	High	Medium	High
On Load procedure	No	Yes	No	Yes
Improved oil properties	No	Yes	Yes	Yes
Stray Gassing Probability	Yes	No	Yes	No
Reliability and Acceptance by OEMs	Reliable, most widely used & accepted by all OEMs	Mixed Response. Not executed by many.	Reliable, accepted by all OEMs	Newer Technique, Limited Knowledge
Maintenance	Periodic replenishment of passivator required	Close monitoring required to ensure stability	Relatively less maintenance expected	Close monitoring required.

3.4 Oil Exchange with addition of metal passivator

For this technique, the complete oil of the asset needs to be replaced with new oil and metal passivators to be added. By removing the old oil, the DBDS can be eliminated.

Based on the above evaluation, at that time it was seen that most OEMs considered this technique as the most reliable technique, which results in removal of DBDS to a level of 85-90%. The balance 10-15% DBDS trapped in the insulation can also be removed to a certain extend by flushing the active part with new oil (typically 10% extra new oil will be required). Moreover, with the addition of metal passivators the risk due to the DBDS retained in the

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insulation system, if any, can be further eliminated. In addition, the other oil properties are renewed.

On the flip side, the cost of oil exchange is the highest compared to other techniques.

This mitigation technique was found most suitable for the 132 kV bus reactors in 400 kV substations which are continuously in service at full load (high temperatures all the time) and since the quantity of oil is not very high it was seen as a good balance between risk performance and cost for these assets.

3.5 Adding Metal Passivator to Existing Oil

Metal passivators chemically adhere to non-enameled, bare copper surface, forming a monomolecular layer (a coating on the surface) that blocks copper involvement as a reactant in the copper sulphide formation and hinders copper catalytic activity as an oxidation catalyst [7] [8] [9] [10] [4]. Metal passivators are polar compounds and have a tendency to be absorbed in the paper and to attach to other metal surfaces. The amount of metal passivator spent for coating other metal surfaces has not been quantified, but is likely to be very small and below the limits of standard deviation for the test method for metal passivator determination. Therefore, it is assumed that negligible amounts of added metal passivator are spent for coating of other metal surfaces, whereas a higher amount is spent for absorption in cellulose materials and this is likely to be more pronounced at elevated temperatures which speed up transport of metal passivator into the paper [11], [5]. Naturally, oil is the transfer medium for transfer of metal passivator to the metal surfaces and into solid insulation of the transformer [4].
Addition of metal passivators to existing oil is by far the most widely used and the most cost effective technique owing to the simplicity and low time required for execution.

However, this technique does not focus on removal of DBDS and can be considered as a temporary solution since DBDS is not removed. Additionally, the passivator content needs to be monitored periodically, since it is consumed (with no standard depletion rate) and if it falls in the poor range, no protection against copper sulphide formation will be offered and the asset will shift back to high risk. Moreover, the oil will remain aged in the condition as it was- no renewal of aging oil properties could be achieved.

This mitigation technique was found most suitable for the 132 kV feeder and bus reactors in 132 kV Substations, which are generally not in service almost for 6 months every year and hence with almost 50% less risk of copper sulphide deposition. Moreover, the cost and execution time required being less, this was found to be a good balance between risk performance and cost for these assets.

3.6 Oil Reclamation

Oil reclamation eliminates or reduces soluble and insoluble polar contaminants, degradation products and also corrosive sulfur compounds from the aged oil by chemical and physical processing using fuller's earth. During the reclaiming process the transformer oil is circulated continuously with the help of a machine which uses special/ proprietary regeneration design. Highly effective adsorption agent, generally reactivatable clay absorb the polar impurities and degradation products from the aged transformer oil and also removes the Corrosive Sulphur compounds. The time taken is dependent on the efficiency of the machine and the amount of DBDS in oil; however it is longer than the time taken for conventional regeneration for removal of aging products. Also the cost is expected to be less than the cost for complete oil exchange.

Considering the criticality and risk of 400 kV transformers, addition of metal passivator to existing oil was not found effective from the performance and risk point of view. Moreover, in case of oil exchange, even if the cost factor is ignored (due to high oil quantity), the residual 10-15% DBDS in the insulation will again pose a risk after some time.

Hence, the best balance between performance, risk and cost for 400 kV transformers was found in utilizing oil regeneration as the mitigation technique. This not only ensures almost complete removal of DBDS, but also is less costly compared to oil exchange.

3.7 Performance of the Mitigation Actions Selected for Assets

As a result of the study carried out by DEWA, based on the criticality and risk assessment, three types of mitigation actionswereidentifiedandcarriedout.Theequipmentwereclassifiedunderthreegroupswitheachgroupbeing applied with one of the mitigation methods as shown in the below table

Group no	Eq Details	Type	Mitigation Action
Group-1	132 kV, 40 MVAr	Shunt Reactor (Bus)	Oil Replacement with addition of metal passivator
	132 kV, 40 MVAr	Shunt Reactor (Bus)	Oil Replacement with addition of metal passivator
	132 kV, 40 MVAr	Shunt Reactor (Bus)	Oil Replacement with addition of metal passivator
	132 kV, 40 MVAr	Shunt Reactor (Bus)	Oil Replacement with addition of metal passivator
Group-2	132 kV, 15 MVAr	Shunt Reactor (Line)	Addition of metal passivator to existing oil
	132 kV, 15 MVAr	Shunt Reactor (Line)	Addition of metal passivator to existing oil
	132 kV, 30 MVAr	Shunt Reactor (Line)	Addition of metal passivator to existing oil
	132 kV, 30 MVAr	Shunt Reactor (Bus)	Addition of metal passivator to existing oil
Group-3	400/132 kV, 450 MVA	Auto Transformer	Oil Regeneration
	400/132 kV, 300 MVA	Auto Transformer	Oil Regeneration

The following are the observations for each asset

a) 132 kV, 40 MVAr Shunt Reactor (Bus)- Oil Replacement with addition of metal passivator

Thereactorwasoriginallysuppliedwithinhibitedoil.Testsdoneindicatedthattheoilwas corrosive with DBDS value measured as 59 and 97 ppm at two different labs. For the process, the oil was drained completely, the active part flushed with new oil. Nypass (passivator) was added to the new oil in a separate storage tank (with target of 100 ppm) and circulated to get a homogeneous mixture. This new oil containing metal passivator was then filled back in thereactor.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/deteriorated as expected for normal aging for more than 5years after the mitigation actions.
2) The IFT dropped to around 80% as measured after 5 years of mitigation actions.
3) The passivator content was found to have dropped to almost 40% of original concentration within 3 years. However, since the DBDS content remained <5 ppm for this three year period, it was carefully concluded that topping up of passivator was not required.
4) There was no stray gassing observed for more than 5 years after mitigation actions.

b) 132 kV, 40 MVAr Shunt Reactor (Bus)- Oil Replacement with addition of metal passivator

The reactor was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 58 and 66ppm at two different labs. For the process, the oil was drained completely, the active part flushed with new oil. Nypass (passivator) was added to the new oil in a separate storage tank (with target of 100ppm) and circulated to get homogeneous mixture. This new oil containing metal passivator was then filled back in the reactor.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 5 years after the mitigation actions.
2) The IFT dropped to around 80% as measured after 5 years of mitigation actions.
3) The passivator content was found to have dropped to almost 40% of original concentration within 3years. However, since the DBDS content remained <5 ppm for this three year period, it was carefully concluded that topping up of passivator was not required.
4) There was no stray gassing observed for more that 5 years after mitigation actions.

c) 132 kV, 40 MVAr Shunt Reactor (Bus)- Oil Replacement Oil Replacement with addition of metal passivator

The reactor was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 42 and 81ppm at two different labs. For the process, the oil was drained completely, the active part flushed with new oil. Nypass (passivator)was added to the new oil in a separate storage tank (withtargetof100ppm) and circulated to get homogeneous mixture. This new oil containing metal passivator was then filled back in the reactor.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 5 years after the mitigation actions.
2) The IFT dropped to around 77% as measured after 5 years of mitigation actions.
3) The passivator content was found to have dropped to almost 65% of original concentration within 3 years. However, since the DBDS content remained <5 ppm for this three year period, it was carefully concluded that topping up of passivator was not required.
4) There was no stray gassing observed for more than 5 years after mitigation actions.

d) 132 kV, 40 MVAr Shunt Reactor (Bus)- Oil Replacement with addition of metal passivator

The reactor was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 51and 89ppm at two different labs. For the process, the oil was drained completely, the active part flushed with new oil. Nypass (passivator) was added to the new oil in a separate storage tank (withtargetof100ppm) and circulated to get homogeneous mixture. This new oil containing metal passivator was then filled back in there actor.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 5 years after the mitigation actions.
2) The IFT dropped to around 92% as measured after 5 years of mitigation actions.
3) The passivator content was found to have dropped to almost 35% of original concentration within 3 years. However, since the DBDS content remained <5 ppm for this three year period, it was carefully concluded that topping up of passivator was not required.
4) There was no stray gassing observed for more that 5 years after mitigation actions.

e) 132 kV, 15 MVAr Shunt Reactor (Feeder)- Addition of metal passivator to existing oil

The reactor was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 72 and 108ppm at two different labs. For the process, part of the existing oil of the reactor was drained in a storage tank. Nypass was added to the storage tank, with a target concentration of 100 ppm of the passivator, and the oil containing metal passivator was circulated in the storage tank for attaining homogeneous mixture. Subsequently the storage tank oil containing metal passivator was circulated with the complete oil of the main tank.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 3 years after the mitigation actions.
2) The passivator content was found be stable over three years after the mitigation actions.

3) There was no stray gassing observed for more that 5 years after mitigation actions.

f) 132 kV, 15 MVAr Shunt Reactor (Feeder)- Addition of metal passivator to existing oil

The reactor was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 53 and 63 ppm at two different labs. For the process, part of the existing oil of the reactor was drained in a storage tank. Ny pass was added to the storage tank, with a target concentration of 100 ppm of the passivator, and the oil containing metal passivator was circulated in the storage tank for attaining homogeneous mixture. Subsequently the storage tank oil containing metal passivator was circulated with the complete oil of the main tank.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 3 years after the mitigation actions.
2) The passivator content was found be stable over three years after the mitigation actions.
3) There was no stray gassing observed for around 5 years after mitigation actions.

g) 132 kV, 30 MVAr Shunt Reactor (Feeder)- Addition of metal passivator to existingoil

The reactor was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 79 and 116ppm at two different labs For the process, part of the existing oil of the reactor was drained in a storage tank. Nypass was added to the storage tank, with a target concentration of 100 ppm of the passivator, and the oil containing metal passivator was circulated in the storage tank for attaining homogeneous mixture. Subsequently the storage tank oil containing metal passivator was circulated with the complete oil of the main tank.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 5 years after the mitigation actions.
2) The passivator content depleted to “poor” range of IEC 60422 within one year of mitigation action. Although the depletion was relatively quick as compared to other units, however, this was not unexpected. Moreover, it is widely known and accepted fact that the passivator content has to be monitored regularly to ensure mitigation of the risk and the almost similar depletion rate for sister unit confirmed that the passivator was performing its intended function and entails the success of the mitigation action.
3) The depletion rate was monitored for sufficient time to ensure that it has stabilized and then the passivator was replenished to the target value again (slightly higher).
4) The replenished passivator was monitored and it was found that the value was in good range of IEC 60422 after one year.
5) There was no stray gassing observed for around 5 years and two phases of mitigation actions.

h) 132 kV, 30 MVAr Shunt Reactor (Bus)- Addition of metal passivator to existing oil

The reactor was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 69 and 113ppm at two different labs. For the process, part of the existing oil of the reactor was drained in a storage tank. Nypass was added to the storage tank, with a target concentration of 100 ppm of the passivator, and the oil containing metal passivator was circulated in the storage tank for attaining homogeneous mixture. Subsequently the storage tank oil containing metal passivator was circulated with the complete oil of the main tank.

The oil properties and DGA were monitored over a period of time and following are the observations:

1) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 5 years after the mitigation actions.
2) The passivator content depleted to “poor” range of IEC 60422 within one year of mitigation action. Although the depletion was relatively quick as compared to other units, however, this was not unexpected. Moreover, it is widely known and accepted fact that the passivator content has to be monitored regularly to ensure mitigation of the risk and the almost similar depletion rate for sister unit confirmed that the passivator was performing its intended function and entails the success of the mitigation action.
3) The depletion rate was monitored for sufficient time to ensure that it has stabilized and then the passivator was replenished to the target value again (slightly higher).
4) The replenished passivator was monitored and it was found that the value was in good range of IEC 60422 after one year.
5) There was no stray gassing observed for around 5 years and two phases of mitigation actions.

i) 400/ 132 kV, 300 MVA Auto Transformer – Oil Reclamation

The transformer was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 42 and 57 ppm at two different labs. For the process, regeneration of the oil was carried out using specially designed machine for removal of DBDS and Corrosive Sulphur by one of the OEM representative with the transformer out of service (offline). No passivator was added to the oil.

The oil properties and DGA were monitored over a 3 year period and following are the observations:

1) The DBDS remained <5 ppm as measured till the end of three years.
2) All oil properties were found to be stable/ deteriorated as expected for normal aging for more than 3 years after the mitigation actions.
3) There was no stray gassing observed for more than 3 years after mitigation actions.

j) 400/ 132 kV, 450 MVA Auto Transformer – Oil Reclamation

The transformer was originally supplied with inhibited oil. Tests done indicated that the oil was corrosive with DBDS value measured as 42 and 61 ppm at two different labs. For the process, regeneration of the oil was carried out using specially designed machine for removal of DBDS and Corrosive Sulphur by one of the OEM representative with the transformer out of service (offline). No passivator was added to the oil.

The oil properties and DGA were monitored over 3-year period and following are the observations:

1) The DBDS exceeded 5 ppm after 6 months of regeneration. It is understood that the DBDS in the oil trapped in the active part insulation (which could not be removed in offline process) was released when the transformer was put back in service. The values of DBDS were monitored for stabilization and upon achieving stability, it was implied that all the DBDS from the windings was removed and a short regeneration was repeated. Based on the successful application of this mitigation method previously, no further issues are expected.
2) All oil properties were found to be stable/ deteriorated as expected fornormalaging for more than 3 years after the mitigation actions.
3) There was no stray gassing observed for more than 3 years after mitigation actions.

4. Conclusion

From the study and implementation of mitigation actions against Corrosive Sulphur and DBDS at DEWA the following can be concluded

1) At DEWA, T(P) has successfully managed to mitigate the effect of Corrosive Sulphur and DBDS using a strategic approach, resulting in tangible and intangible benefits in a cost effective manner. The success of the study and the selection of mitigation actions for its assets is validated by the satisfactory test results and satisfactory operation of the assets till date.
2) Oil exchange with addition of metal passivators is a preferred mitigation technique for high risk assets having lower oil volumes (carrying out a cost benefit compared to oil reclamation is highly recommended).Moreover, since the complete oil is replaced, all the oil properties are renewed and the aging of oil is also taken care of. In addition the technical drawback of this technique that 10-15% of DBDS trapped in the insulation is released later on is taken care of by flushing the active part and the addition of metal passivators, which prevent any further copper sulphide formation.
3) Adding metal passivators to existing oil is an efficient and cost effective solution in case of assets where the operator has flexibility on reconsidering asset loading strategies or where already the asset is not heavily loaded. However the passivator content has to be monitored regularly and passivation does not attack the DBDS in oil. This technique is not recommended for assets under high risk, especially if these are very critical to the network/plant.
4) Oil reclamation is one of the best techniques in case of mitigation action on large transformers. However, the selection of the right service provider is of the utmost importance, since there have been several occurrences where the oil has become more corrosive after the intervention [5].

It is evident that no single mitigation action suits all assets and each utility/ industry needs to take into consideration various factors related to the current condition of the asset, the loading strategies, the lifecycle management and the cost factors.

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References

[1] BS EN ISO 62535 Test Method for detection of potentially Corrosive Sulphur in used & unused insulating oil Edition 1.02009-01
[2] IEC 62697-1 Test Method for qualitative determination of Dibenzyle DiSulphide (DBDS) Edition 1.0 2012- 08
[3] Lance R. Lewand, The Role of Corrosive Sulfur in Transformers and Transformer Oils, Doble Engineering Company, USA,2012
[4] CIGRE WG A2-40, "Copper sulphide long term mitigation and risk assessment," Final Report No625,2015
[5] CIGRE WG A2-32, "Copper sulphide in transformer insulation," Final Report, Brochure 378,2009.
[6] LiuY., .J.,HuE.D., HuangJ.J.: 'Effects of antioxidants and acids on copper sulfide generation and migration induced by dibenzyl disulfide in oil immersed transformers', IEEJ Trans. Electr. Electronic Eng., 2015.
[7] Scatiggio, F., Pompili, M.; Bratnikas, R. Oils with Presence of Corrosive Sulphur: Mitigation and Collateral Effects. Proceedings of IEEE Electrical Insulation Conference, Montreal, 2009; 478-481.
[8] Amimoto,T.; Nagao, E.;Tanimura,J.; ToyamaS.;Yamada N.Duration and Mechanism of Suppresive Effect ofTriazole-based Passivators on Copper-sulfide Depositionon insulating paper. IEEE Trans.Dielectr.Electr. Insul. 2009, 16,257.
[9] Wiklund, P.; Levin, M.; Pahlavanpour, B. Copper Dissolution and Metal Passivators in Insulating Oil. IEEE Electrical Insulating Magazine 2007, 23(4),1.
[10] Facciotti,M.;Amaro,P.S.;Brown,R.C.D.;Lewin,P.;Pilgrim,J.A.;Wilson,G.andJarman,P.N."Passivators, Corrosive Sulphur and surface chemistry. New tools in the investigation of an effective protection." My Transfo proceedings, November2014
[11] Jelena M. Lukic, Srdjan Milosavljevic and Aleksandar M. Orlovic, Degradation of the Insulating System of Power Transformers by Copper Sulfide Deposition: Influence of Oil Oxidation and Presence of Metal Passivator, Ind.Chem.Res. 2010, 49,9600-9608.